Studies of rare production and decay processes of the Higgs boson at the ATLAS experiment

Proklova N.
on behalf of the ATLAS Collaboration

Phenomenology 2020,
05.05.2020
Introduction

Many Higgs boson decay channels/production modes have been discovered and measured → consistent with the SM within uncertainties

- **BUT**: BSM physics may still manifest itself in the Higgs sector.
- Rare or forbidden decays provide novel probes to new physics

- **Rare decays**: searches of $H \rightarrow Z\gamma$, $H \rightarrow ee$ and $H \rightarrow \mu\mu$, CP properties probe with $ttH+tH$, $H \rightarrow \gamma\gamma$
- **Forbidden decays**: vanishing in the SM, e.g. flavour violating decays $H \rightarrow e\tau/\mu\tau$, $H \rightarrow e\mu$
**ttH+tH, H→γγ – CP properties**

SM Higgs boson is CP-even: $J^{CP} = 0^{++}$

But ttH&tH processes allow to probe CP-violation in the top-Yukawa coupling at tree level:

$$\mathcal{L} = - \frac{m_t}{\nu} (\bar{\psi}_t \kappa_t (\cos(\alpha) + i \sin(\alpha) \gamma_5) \psi_t) H$$

**Parameters of Interest:**
- $\kappa_t$: top-Yukawa coupling parameter
- $\alpha$: CP-mixing angle

SM: $\kappa_t = 1, \alpha = 0$
CP-odd: $\alpha = 90^\circ$

CP-odd component can have effect on cross sections and kinematics of ttH/tH

$H→γγ$ has clean signature and excellent sensitivity
**ttH+tH, H→γγ CP: Analysis strategy**

**Data : full Run 2 , 139 fb⁻¹**

**Event selection:**
- 2 tight, isolated photons, ≥ 1 b-tagged jet
- Two regions:
  - Hadronic: \( N_{\text{jets}} \geq 3, N_{\text{lep}} = 0 \)
  - Leptonic: \( N_{\text{lep}} \geq 1 \)

**Categorisation:**
1) **Bkg. rejection BDT** to separate ttH like events from continuum bkg (non tight isolated data)
2) **CP BDT** – separate CP-even ttH/tH from CP-odd
   - 20 kinematic / angular / event variables + dedicated BDT to reconstruct top quarks
3) Event Categorisation (20 categories) based on 2D plane of BKG and CP BDTs

**Signal extraction:**
Simultaneous fit in all 20 categories to myγ distribution
ttH+tH, H→γγ CP: Results

**ttH significance:**
signal strength: $1.4 \pm 0.4$(stat)$\pm 0.2$(sys)
obs. (exp.) sign.: $5.2\sigma$ ($4.4\sigma$)

**tH cross section upper limit:**
obsv. $< 12 \times$ SM at 95% CL

H→γγ (and ggH) rates constrained to combination results

$|\alpha| > 43^\circ$ excluded at the 95% CL
(expected exclusion: $|\alpha| > 63^\circ$)

CP-odd hypothesis rejected:
at $3.9\sigma$ (expected : $2.5\sigma$)
H$\rightarrow$$\mu$$\mu$ decay search

H$\rightarrow$$\mu$$\mu$ is a sensitive channel to explore the Higgs boson coupling to the second generation of fermions

**BUT**: $\text{BR}_{\text{SM}}=2.2 \times 10^{-4}$ and large background

- Experimentally **clean & good mass resolution**
- Signal would appear as a peak in $m_{\mu\mu}$ on top of smoothly falling distribution that mainly consists of Drell-Yan process

In a $110 < m_{\mu\mu} < 160$ GeV window:

- ~2.5M events in data (139 fb$^{-1}$) mostly from Drell-Yan ($Z/\gamma^* \rightarrow \mu\mu$)
- Expected S~860 events ($\varepsilon=60\%$)
H→μμ decay search

Analysis strategy
- BDT-based categorization to increase signal sensitivity (based on the production mode)
- Data driven approach used for bkg estimation
  Spurious signal (SS) estimated with large statistics fast-Sim (~700 times the data luminosity)
- S+B PDF used to fit the observed m_μμ spectra simultaneously in all the categories to derive the final signal strength μ

Signal and bkg modelled by analytic functions

Results
No significant excess:
0.8σ obs (1.5σ exp)
μ = 0.5±0.7 (1.0±0.7 exp.) ->
μ < 1.7 @95% CL (2.2 exp)

Statistically limited
Neutrinos oscillations indicate that the LFV exists → lepton flavour is not an exact symmetry → Possibility for BSM physics

Many theoretical models allow the LFV Higgs currents:

- $H \rightarrow e\tau / H \rightarrow \mu\tau$: $BR(H \rightarrow \tau l) \leq O(1\%)$
- $H \rightarrow e\mu$: Indirect constraints set via $\mu \rightarrow e\gamma$, but these constraints rely on SM assumptions for $Y_{ee}$ and $Y_{\mu\mu}$

$BF(H \rightarrow ee)$ is below sensitivity of the LHC due to very small $Y_{ee}$ and large background

**BUT**: LHC is still most sensitive way to set constraints on this coupling

Very similar to $H \rightarrow \mu\mu$ search, with similar signal efficiencies and backgrounds

arXiv:1907.06131  arXiv:1909.10235  H$\rightarrow$ee/H$\rightarrow$e$\mu$ results provided by the same group
**LFV with H→eτ/H→μτ/H→eμ and H→ee**

No significant signal observed for any decay

H→eτ/H→μτ:
- BR(H → eτ) < 0.47% (0.34% expected)
- BR(H → μτ) < 0.28% (0.37% expected)

H→eμ:
- B(H → eμ) = (0.4 ± 2.9) × 10^{-5}
  95% CLS limits for obs. (exp.):
  - 6.2 × 10^{-5} (5.9 × 10^{-5})

H→ee:
- B(H → ee) = (0.0 ± 1.8) × 10^{-4}
  95% CLS limits for obs. (exp.):
  - 3.6 × 10^{-4} (3.5 × 10^{-4})
H→Zγ decay search

- more difficult than Higgs→γγ
  -(B[H→Zγ]xB[Z→ee/μμ]= ~10⁻⁴)
- **BUT**: Small background → great sensitivity

**Sensitive to new physics through the loop diagrams (may contain new charged particles)**

Focus only on Z→ee/μμ decays as they have good invariant mass resolution and background rejections

**BUT**: less signal than H→yy

arXiv:1708.00212
H→Zγ decay search: Analysis strategy

Event selection
- 2 leptons, pT > 10 GeV
- + 1 photon, pT > 10 GeV
- |m_ll - m_Z| < 10 GeV
- 115 < m_llγ < 170 GeV

Categorisation
- MVA VBF-like category + 5 cut-based categories
- Significance improves by >40% vs the inclusive case

Signal
- VBF, ggH, VH, ttH processes in each category sharing the same fixed DSCB model

Background
- Zy + Z+jets: parametric models and fit ranges selected to maximise the expected significance
H→Zγ decay search: Results

The total uncertainty is dominated by the **statistical component** (43%) of data, with a large contribution from the spurious signal systematic uncertainties (15%).

**For m_H = 125.09 GeV:**

- **Best fit signal strength**
  \[ \mu = 2.0^{+1.0}_{-0.9} = 2.0^{+0.9}_{-0.9}(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) \text{ (obs.)} \]
  \[ \mu = 1.0^{+0.9}_{-0.9} = 1.0^{+0.8}_{-0.8}(\text{stat.})^{+0.3}_{-0.3}(\text{syst.}) \text{ (exp.)} \]

- **Limits on μ at 95% CL:**
  Obs.: \( \mu < 3.6 \)
  Exp: \( \mu < 1.7 \) (2.6) assuming no (SM) H→Zγ

- **BR(H→Zγ) < 0.55% at 95% CL**
  \( \sigma \cdot \text{BR} < 305 \text{ fb at 95% CL} \)
Rare or forbidden Higgs boson decays are presented
- $H \to Z\gamma$
- $H \to ee$
- $H \to \mu\mu$
- $H \to l\tau$
- $H \to e\mu$
Sensitive to the physics beyond Standard Model

- No significant excess seen
  Most of the analyses are still statistically limited

+ CP property constraints of the top Yukawa coupling with $ttH+tH$ process and $H \to \gamma\gamma$ decays

Looking forward to Run3
Lepton-flavour-violation with $H\rightarrow e\tau/H\rightarrow \mu\tau$

Analysis strategy
- Using MC and data-driven background to estimate SM bkg (SM $H\rightarrow \tau\tau$ is background)
- 2015+2016 dataset (36 $fb^{-1}$)
- Two independent channels:
  - $H\rightarrow e\tau$ or $H\rightarrow \mu\tau$ considering both tau decay to leptons ($\tau_l$) and with hadrons ($\tau_h$)
- MVA performed to enhance the signal/bkg separation: BDT output used to perform a shape analysis of the data
- Analysis categories:
  - VBF category (VBFH): $n_{jets} \geq 2$, high $m_{jj}$
  - Non-VBF category (dominated by ggH)
- Exploited the jet kinematics, the leptons momentum disparity and the mass reconstruction
- Two Control Regions defined for the $\tau_{lep}$ sub-channel to constrain top and $Z\tau\tau$ bkg
- Limits set on BR $H\rightarrow e\tau$ and BR $H\rightarrow \mu\tau$ separately
**H→ee and H→eµ decay searches**

**Analysis strategy**

- Data driven analysis; MC only used for signal shape fit and spurious signal fit in H→ee
- Event categorisation: 7 (8) categories for ee (eµ)
- The signal appears as a peak on top of a smooth background in the mll spectrum
- Signal parameterised as Crystal Ball + Gaussian for both decay channels
- Background parameterised as (Voigtian + exp[am||]/m||^3) for ee, Bernstein polynomial for eµ
- Systematics accounted for as nuisance parameters in final fit
- Limits calculated from fit using CL_s method